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Quantifying Seepage and Evaporation Loss Reductions through Canal Lining: A Field Study from Nakada, Egypt

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Canal Lining, Seepage, Evaporation, Water Losses.

Abstract: This study investigates the impact of canal lining on agricultural water efficiency in Nakada, Egypt, by analyzing seepage and evaporation losses. The study area irrigation network covers a length of 110 kilometers and serves an area of 98,600 hectares of agricultural land. Findings reveal a significant 81% reduction in seepage losses due to lining, reduction from an average of 4,776 m³/day for unlined sections to 906 m^3/day for lined sections in Nakada canals network with annual working days (210 days). Using empirical formulas and field ponding tests, the study calibrated seepage models to reflect local soil and canal conditions. Furthermore, evaporation losses also recorded measurable improvement, underscoring the effectiveness of canal rehabilitation in enhancing water management. The study provides a reproducible framework for quantifying water savings in arid regions and offers data-driven recommendations for water policy and canal rehabilitation programs. While emphasizing long-term sustainability, operational efficiency, and the integration of field-based hydraulic assessments.

1. Introduction

According to estimations provided by the World Bank, Egypt possessed a grand sum of 58.8 billion cubic meters (BCM) of renewable water resources in the year 2017. Nevertheless, Egypt's annual outflow of freshwater amounted to 62.6 BCM, signaling excessive exploitation of the nation's water resources [1,2]. The agricultural domain serves as the primary consumer of water in Egypt, constituting approximately 85% of the overall water extraction, while the household and industrial sectors collectively account for the remaining 15%. However, the agricultural sector exhibits suboptimal water usage efficiency due to ineffective irrigation techniques and outdated infrastructure, resulting in the squandering of this valuable resource [3,4].

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The irrigation system in Egypt is widely regarded as one of the most ancient globally, comprising primary and secondary canals with a total length spanning an impressive 33,500 kilometers. Regular maintenance has been carried out since the initial establishment of this intricate canal network to ensure its hydraulic efficacy and capacity to effectively distribute water. Nakada, a region in Upper Egypt is heavily relies on irrigation canals as the primary water source [4,5].

Recently, Egypt has faced numerous water-related issues, including population growth, climate pattern alterations, and complexities arising from upstream water resource exploitation by Nile Basin countries. Nations upstream such as Ethiopia are constructing dams on the Nile's tributaries, potentially limiting downstream access to water [6,7]. Consequently, the state resolved to streamline water usage, construct canal linings, and investigate water depletion origins in channels, constrained by various factors, notably seepage losses via canal boundaries and bed, as well as evaporation losses from water surfaces [8,9]. Seepage losses constitute approximately 98.37% of total conveyance losses, while evaporation represents roughly 0.3% of complete stream loss [9,10]. This paper aims to quantifying seepage and evaporation loss reductions through canal lining in Nakada, Qena Governorate, Upper Egypt, including benefits, drawbacks, methodologies, key performance indicators, and origins and magnitudes of water depletion in select irrigation canals. The study investigates sources of water loss, whether through seepage and evaporation, and variables influencing each mechanism, along with methodologies employed to quantify their respective volumes. Additionally, the study provides recommendations aimed at mitigating water loss from irrigation canals.

1.1 Rehabilitating and Lining Canals

Rehabilitating canals involves rectifying canal structures that have been impaired or degraded due to factors like erosion, sedimentation, and waterlogging. Regular maintenance and timely restoration of canals are indispensable to ensure their operational efficiency and long-term viability. Canal lining entails applying an impermeable or low-permeability substance to the canal's inner surface. This technique is extensively employed to mitigate waterlogging and reduce seepage losses. Lined canals have a larger capacity due to their smoother surfaces and higher water velocities, which in turn reduces evaporation and prevents weed growth, thus improving conveyance efficiency [11,12]. Canal lining and rehabilitation play crucial roles in maintaining and improving the efficiency and longevity of irrigation canals, significantly aiding in water conservation and promoting sustainable agricultural practices. It can be applied to the entire canal's perimeter or targeted to specific parts such as the bed or sides. Several materials are employed for preventing seepage in canals as shown in Fig. 1, including puddle clay, earthen materials, rubble masonry, asphaltic concrete, geo-synthetics, and concrete [13].

1.2 Losses of Water in Canals

1.2.1 Losses Due to Seepage

Seepage in canals occurs when water infiltrates through the canal boundaries, including the bed and sidewalls, influenced by factors like soil permeability, groundwater level, hydraulic conditions, water pressure, and canal depth. The consequences of seepage can be significant. Seepage results in the loss of water from the canal, impacting water availability for agriculture and other uses, particularly in water-scarce regions [14,15]. It can also saturate the soil near the canal, affecting its structure and stability, leading to erosion and instability [16].Furthermore, seepage contributes to environmental degradation by accumulating salt in the soil and altering groundwater levels, negatively affecting soil fertility, plant growth, and biodiversity [17].Additionally, seepage can erode the canal bed and sidewalls, potentially causing sinkhole development and shortening the canal's service life, thereby increasing maintenance costs [18,19].

Plain Concrete and Pitching | Reinforced Concrete | Concrete Canvas

Geo-textile Mattresses | Geo-membranes | Geo-cell

Figure 1. Canal Lining Types [20].

1.2.2 Seepage Estimation

1.2.2.1 Empirical techniques

The empirical estimation and technique are based on the relationships generated between effective parameters, which are the results of field studies or lab observations and measurements. Various empirical equations and techniques are used to measure the seepage losses in irrigation canals, such as the Molesworth-Yennidumia (Egyptian Method), the Indian formula, the Moritz Equation, the Ingham equation, Nazir Ahmad, Lacey's equation, and the Farouk equation [3].

Molesworth-Yennidumia (Egyptian Method): The Molesworth-Yennidumia employs a formula considering canal length, wetted perimeter, hydraulic radius, and soil type:

$$S = C \cdot L \cdot P \cdot \sqrt{R} \qquad (1)$$

Where S is the seepage rate ($m^3/sec/km$), L denotes the canal length (*m*), P is the wetted perimeter (*m*), R refers to the hydraulic radius (*m*), and C is a soil-dependent constant. The value of constant C was assumed to be 0.003, 0.0015, 0.0018, 0.0022, and 0.0026 for sandy loam, clay, silty clay, clay loam, and silty loam, respectively [21].

Indian formula: The Indian formula estimates seepage losses based on canal width, slope, water depth, velocity, discharge, and soil type:

$$S = C \cdot a \cdot H \tag{2}$$

Where S is the total seepage losses (*ft^3/sec*); "a" is the area of the wetted perimeter (*million ft^2*); H is the water depth (*ft.*); and C is a soil-dependent factor ranging between 1.1 and 1.8 [10].

The United States Bureau of Reclamation technique (USBR) (Moritz Equation): This method utilizes the Moritz method based on discharge, velocity, and soil type.

$$S = 0.2 \cdot C \cdot \sqrt{Q/V} \tag{3}$$

Where S is the seepage loss (*ft^3/s/mile*), Q is the discharge (*ft^2/sec/mil*), V is the mean velocity (*ft/sec*), and C is a constant determined by soil type, the values of C are as follows: 0.34 for cemented gravel and hardpan with sandy loam, 0.41 for clay and clayey loam, 0.66 for sandy loam, 1.68 for sandy soil with rock, and 2.20 for sandy and gravelly soil [21].

Ingham equation: This equation estimates seepage rates by considering the wetted perimeter, length, water depth, and soil type [21].

$$S = 0.55 \times 10^{-6} \times C \times P \times L \times H^{0.5} \tag{4}$$

Where: S represents the seepage rate (*m^3/sec*); *P* is the wetted perimeter (*m*), *L* denotes the channel length (*m*); *H* is the depth of the water in the channel (); and C is a soil-dependent coefficient, with values ranging from 1.5 to 5.5.

Nazir Ahmad: This equation calculates the seepage losses "*S*" (*m^3/sec/km*); as a function only of the flow discharge "Q" (*m^3/sec*) [10].

$$S = \frac{0.04Q^{0.68}}{56.81} \tag{5}$$

Although calibration of empirical formulas, such as those by Moritz, Ingham, and Nazir Ahmad, is used to fit local uses, only a few studies adjust them to the field conditions in Egypt. This study attempts to fill this gap by utilizing field data obtained from the Nakada canal system to improve seepage loss estimation in local settings.

1.2.2.2 Analytical Methods

Analytical approaches entail estimating seepage using mathematical models. The Dupuit-Forchheimer method, along with the Molesworth and Yennidunia approaches, are among the most widely utilized analytical methods for evaluating canal seepage. In Dupuit-Forchheimer, two-dimensional and steady-state flow with homogeneous soil permeability are considered for estimating the seepage rate based on the hydraulic gradient and permeability [4]. Molesworth and Yennidunia's method were mainly based on empirical data and critical factors such as soil hydraulic conductivity, canal slope, and cross-sectional area. This technique is particularly advantageous when obtaining direct seepage measurements [22].

1.2.2.3 Numerical Methods

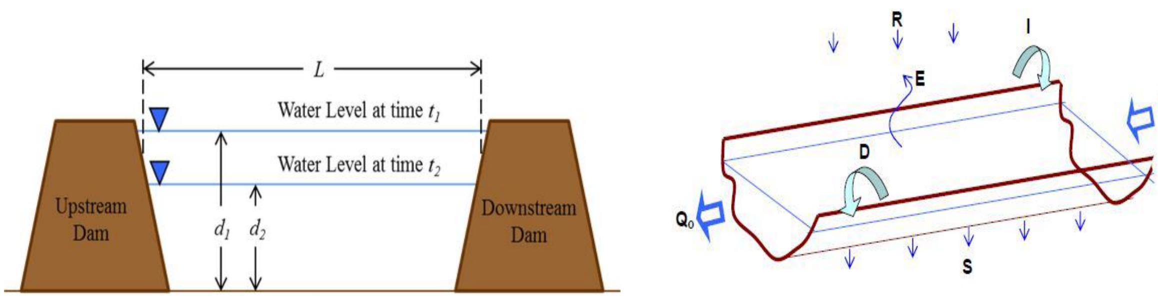
Numerical methods involve computer-based models to simulate water systems such as the seepage process in canals. These techniques play a key role in seepage estimation by solving the governing equations of the water flow and transportation in the soil-canal system considering other critical factors such as soil characteristics, groundwater level, and canal water level. Therefore, a combination of different numerical models can be used widely to obtain more accurate seepage estimation [23].

1.2.2.4 Field Methods

Field methods involve direct measurements of seepage rates using seepage meters placed directly in canals or soil columns. Crucial factors such as soil characteristics (soil type, physical and chemical properties, and hydraulic conductivity), groundwater level, and canal water level are essential and considered [24].The most common field methods are as follows:

Inflow-outflow measurement methods: This method directly measures the flow rates into and out of a canal reach, accounting for upstream inflow, downstream outflow, diverted flow, and evaporation. It requires steady flow conditions and long canal reaches for accurate results[25].

Ponding tests: Ponding tests are performed to detect leaks or seepage in canals. A segment of the canal is isolated and filled with water, then monitored for a decrease in water level over time, indicating seepage. This method, while accurate, necessitates shutting down the canal for testing, can take several days, and may incur construction costs [21,26]. The ponding method offers greater accuracy compared to the inflow-outflow method. However, the choice of appropriate method for a specific project also depends on numerous factors, such as the project's nature, time availability, the magnitude of seepage loss, and available equipment [27].



(a) (b)

Figure 2. Field Methods: (a) Ponding test method, and (b) inflow outflow method [21,27].

1.2.3 Losses Due to Evaporation

Evaporation from canal surfaces contributes to water losses. The evaporation losses are relatively minor compared to seepage losses and typically range between 0.25 % and 1.0 % of the total canal discharge. It is still significant in arid regions and is influenced by factors like temperature, humidity, wind speed, and solar radiation. The evaporation losses can influence water availability, water quality, and the surrounding environment [28]. In addition to these consequences, evaporation can also affect the environment by altering the microclimate surrounding the canal and depleting the water level in adjacent groundwater aquifers. These environmental impacts, in turn, can have implications for soil fertility, plant development, and regional biodiversity [21]. Canal evaporation mitigation can be effectively achieved through various approaches such as canal covering and canal shading. Water management strategies also play a crucial role in canal evaporation control by minimizing the exposed water surface area and controlling the canal water level [29].

1.2.4 Evaporation Estimation

Several methods are commonly employed to estimate evaporation losses from canals, including the evaporation pan method, water balance method, heat balance method (energy balance method), and the aerodynamic method [29]. The rate of evaporation from a moving water surface is influenced not only by the surface wind speed but also by the flow speed. The evaporation rate from pans filled with water can be easily determined through evaporation pan tests. The amount of water evaporated during a specific period (mm/day) corresponds to the decrease in water depth during that period in the absence of rainfall. This method enables the measurement of the combined effects of radiation, wind, temperature, and humidity on evaporation from an open water surface [29]. According to Eq. (6), the total evaporation losses of water in irrigation canals (RE) (m^3/day) from the intake to the fields through the total canal length could be estimated using one of the following equations:

$$RE = (K_p \times E) \times T \times L \tag{6}$$

In which K_p is the pan coefficient; E is the evaporation rate (m^3/day); T is the top width of the canal water surface (m); and L is the total canal length (m) [21,29].

2. Study area

This study focused on the Nakada canals network, Nakada Irrigation Engineering Division, Qena Governorate, Egypt, as shown in Fig. 3. The network extends approximately 110 km and serves a cultivated area of about 23,214 acres. The primary crops are sugarcane and wheat, both irrigated using traditional surface methods, based on an irrigation operation period of 210 days per year. In the study area, sugarcane is a perennial crop cultivated throughout the year, consuming approximately 6,900 m^3/acre/year. In contrast, wheat is a winter crop only, with an average water consumption of around 1,150 m^3/acre/year during its growing season. Soil samples were collected along the canal's examined courses to investigate soil type, composition, and permeability, showing that the soil type is clay, characterized by high plasticity and low permeability, which significantly influences seepage behavior. The total daily discharge for the studied canals regions (Ganapyt Asmant, Ganapyt Beshlaw, Danfiq El-Gharbia, Danfiq El-Sharkia) is 304,992, 214,272, 108,8640, and 164,8512 m³/day, respectively, with a total discharge of 3.25 Mm³/day. Table (1) shows the geometric dimensions of the studied canals for designed cross sections, actual and lined cross sections, while table (2) shows the meteorological observation for the studied area.

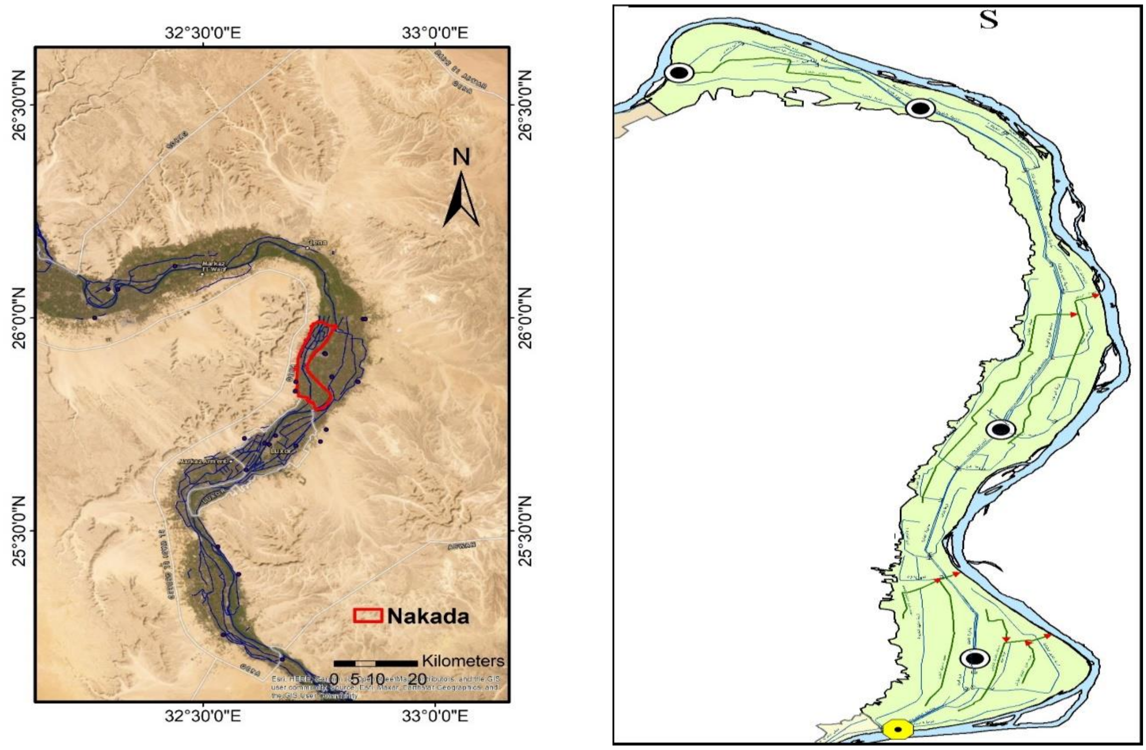


Figure 3. Nakada branch canal and its canals network.

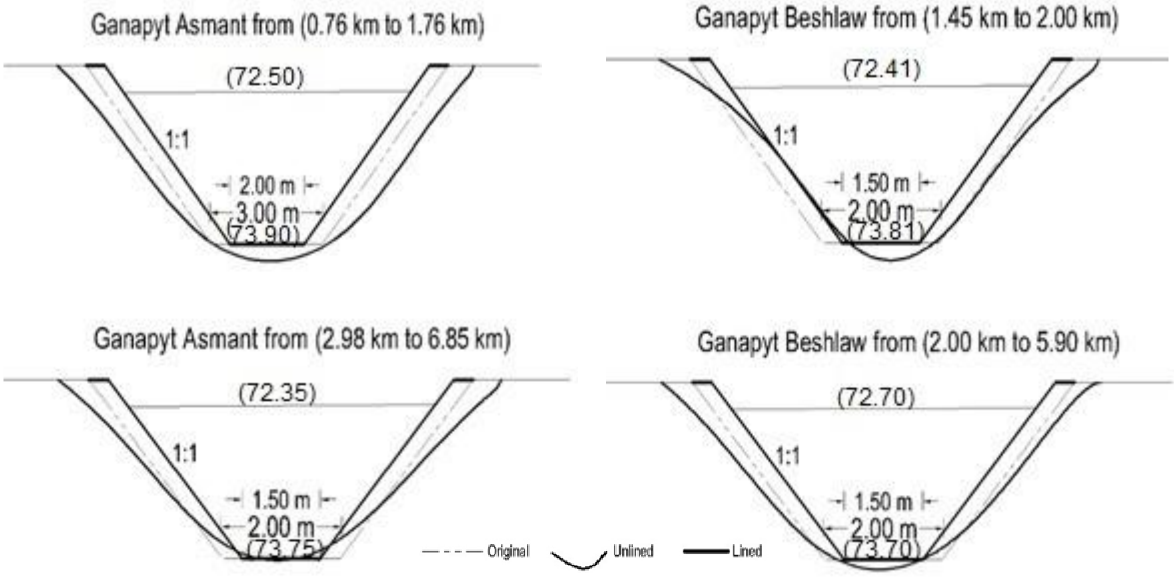


Figure 4. Canal's cross-sections.

Table 1: Geometric dimensions of the studied canals, (Field Data, 2023).

Canal	Section			Side Slope	Original			Unlined			Lined		
	No.	From (*Km*)	To (*Km*)		Bed Width (m)	Water Depth (m)	Discharge (m^3/s)	Bed Width (m)	Water Depth (m)	Discharge (m^3/s)	Bed Width (m)	Water Depth (m)	Discharge (m^3/s)
Ganapyt Asmant	1	0.00	0.76	1:1	3.00	1.40	1.41	4.00	1.80	1.41	3.00	1.40	1.16
	2	0.76	1.76	1:1	3.00	1.40	1.06	3.50	1.65	1.06	2.00	1.40	0.87
	3	1.76	2.98	1:1	2.00	1.40	0.71	3.50	1.55	0.71	1.50	1.40	0.58
	4	2.98	6.85	1:1	2.00	1.40	0.35	3.00	1.40	0.35	1.50	1.40	0.29
Ganapyt Beshlaw	1	0.00	1.46	1:1	2.00	1.00	1.24	3.00	2.00	1.24	2.00	1.00	1.02
	2	1.45	2.00	1:1	2.00	1.00	0.83	2.50	1.50	0.83	1.50	1.00	0.68
	3	2.00	5.9	1:1	2.00	1.00	0.41	2.00	1.00	0.41	1.50	1.00	0.34
Danfiq El Gharbia	1	0.00	0.80	1:1	4.00	1.90	5.04	5.00	2.90	5.04	3.50	1.40	4.14
	2	0.80	3.50	1:1	4.00	1.40	3.78	4.50	2.60	3.78	3.00	1.40	3.11
	3	3.50	6.05	1:1	3.00	1.40	3.16	3.50	1.90	3.15	2.50	1.40	2.71
	4	6.05	9.60	1:1	2.00	1.39	2.26	3.00	1.40	2.26	1.50	1.40	1.84
Danfiq El Sharqia	1	0.00	0.66	1:1	5.00	1.55	4.24	6.00	2.00	4.24	4.00	1.55	3.49
	2	0.66	1.00	1:1	4.00	1.55	3.71	5.50	1.85	3.71	3.50	1.55	3.05
	3	1.00	1.20	1:1	4.00	1.55	3.18	4.50	1.70	3.18	3.00	1.55	2.61
	4	1.20	4.20	1:1	4.00	1.55	2.65	4.50	1.65	2.65	3.00	1.55	2.18
	5	4.20	4.80	1:1	3.00	1.55	2.12	4.00	1.65	2.12	2.50	1.55	1.74
	6	4.80	6.06	1:1	3.00	1.55	1.59	3.50	1.55	1.59	2.50	1.55	1.31
	7	6.06	6.30	1:1	3.00	1.55	1.06	3.00	1.55	1.06	2.50	1.55	0.87
	8	6.30	10.62	1:1	3.00	1.55	0.53	3.00	1.55	0.53	1.50	1.55	0.44

Table 2: Meteorological data of Nakada Area. [31]

Month	Max. Temp. (C°)	Min. Temp. (C°)	Avg. Temp. (C°)	% RH max	Pan Evap. (*mm/day*)	Wind speed (*km/h*)	Sunny hours (*hrs./day*)
Jan.	22	8	15	46.59	6.1	12.5	10.7
Feb.	25	9	17	36.65	6.7	13.4	11.3
March	29	13	21	26.97	7.2	14.2	12
April	34	18	26	20.63	8.4	14.5	12.8
May	38	22	31	17.8	9.6	15.4	13.4
June	41	55	33	18.69	10.3	16.6	13.8
July	41	26	34	20.91	10.8	15.9	13.6
August	40	26	33	22.02	11	16	13
Sept.	38	24	31	26.72	8.7	15.2	12.3
Oct.	34	20	27	32.91	7.4	12.9	11.5
Nov.	28	14	21	44.01	6.4	12.2	10.9
Dec.	24	9	16	49.23	6.2	12.1	10.5

3. Methodology and Field Measurement

To assess the canal’s water losses, a field Ponding Test, an effective method to measure water losses, has been conducted for both lined and unlined canals. The test involved constructing two dams 100 m apart within the canal to allow accurate measurement of seepage losses over a known area and volume. The test duration was 24 hours, conducted during a low-demand irrigation season to minimize external influences and ensure more stable measurement conditions. This setup isolates the test section hydraulically, ensures water stagnation, and allows for precise monitoring of water level decline, which is essential for applying the ponding method. The site was carefully selected, and the necessary tools, including dams and measurement devices, were prepared. To ensure greater accuracy in the results and analysis, all relevant dimensions such as the canal's water depth, bottom width, surface water width, and side slope were verification that there were no leaks through continuous visual inspection along the canal section and dam during the ponding test and there was not water escape or wet spots were observed. The controlled area water levels were measured and recorded at the initial, one-hour interval, and the end. These measures could effectively measure water loss in lined and unlined states, providing a deeper understanding of the lining's effects on water conveyance efficiency and highlighting its importance for enhancing water resource management and reducing losses.

Soil samples systematically were collected every three kilometers along the canal path, specifically from both the canal bed and the adjacent side slopes. This collection aimed to analyze soil types, properties, and permeability; the results were clay to silty clay. Additionally, key parameters and coefficients used in the empirical equations relevant to this study were identified, improving the accuracy and reliability of the findings related to water losses and effective canal management.

Figure 5. Field Measurements.

4. Results and Discussion

4.1 Seepage Losses

The seepage losses for original, existing unlined, and lined cross-sections of Nakada canals were determined through the application of the Egyptian formula, Mortiz's formula, Ingham's formula, and Nazir Ahmad's formula [12]. Also, comprehensive field measurements were conducted for 100 m stretches of the canals under study. As shown in Tables (3) and Fig. (6), significant variations and differences exist in seepage loss values calculated using empirical formulas. These differences were also observed between the field and actual cross-section measurements and those calculated from executive design sheets. The calculated total seepage losses for the four selected canals of Nakada regions (Ganapyt Asmant, Ganapyt Beshlaw, Danfiq El-Gharbia, Danfiq El-Sharkia) with a total length of 32 km original dimensions range from 5,007 to 10,735 m^3/day, with an average value of 6,979 m^3/day (2,54 Mm^3/year). For the existing unlined canals, the seepage losses range from 4,130 to 11,154 m^3/day, with an average value of 8,301 m^3/day (3.02 Mm^3/year).

In the case of the Egyptian formula, it was found that adjusting the C coefficient from 0.0015 to 0.0017 for lined concrete yielded more accurate results, closely aligning with field study measurements. Moreover, the formulas proposed by Mortiz, Ingham, and Nazir Ahmad are based on the unlined condition of canals. Consequently, corrections and the addition of specific coefficients for lined concrete were applied, improving accuracy. For Mortiz's equation, C=0.056; for Ingham's equation, C=0.114; and for Nazir Ahmad's equation, C=0.032. These adjustments produced results that closely matched field observations. The designed lined canal exhibited the lowest seepage losses which range from 697 to 2349 m^3/day, with an average value of 1,575 m^3/day (0.٣٣ Mm^3/year). A significant amount of water, about 6,726 m^3/day, is wasted because of discrepancies between the unlined and lined sections. Seepage losses represent almost 4.1% to 18% with an average of 11% of total discharge for the original designed sections, 4.5% to 21.3% with an average of 12.6% for the existing unlined sections, and 3.4% to 7.5% with an average of 5.4% of the lined sections.

As shown in Figures (4 & 5) and Table (4), the evaluation of the seepage loss using the Egyptian method consistently produces the most accurate calculated values of the seepage loss, recording a total seepage of 33,207 and 6,302 m^3/day for the unlined and lined canals, respectively. This indicates that the canal's lining could reduce the seepage water loss by 81% (26,905 m^3/day).

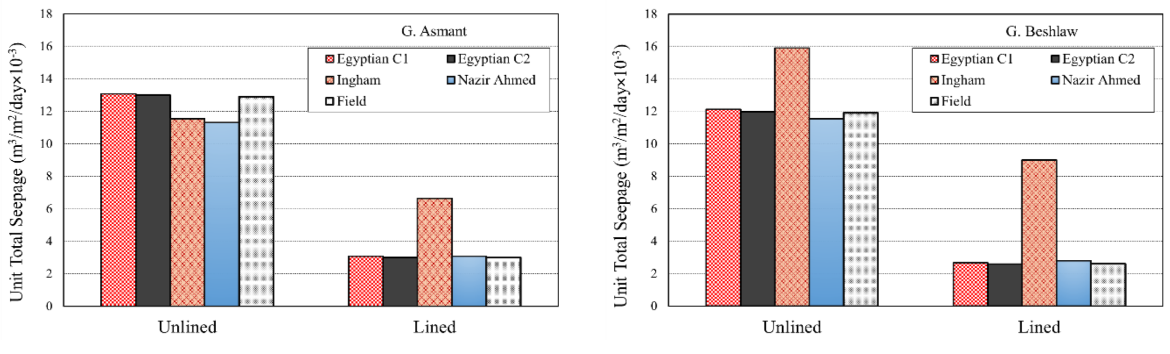


Figure 6. Unit seepage losses, calibration between the empirical formulas and field measurements (Where; reach length = 100 m, C_1=0.0015 & C_2=0.0017).

The unit seepage losses, the seepage loss per the square meter of the wetted perimeter, for the original sections calculated by the empirical formulas range from 110 to 182 $\times 10^{-3}$ m^3/m^2/day, with an average of 150$\times 10^{-3}$ m^3/m^2/day. For the existing unlined canals, the unit seepage losses almost range from 121 to 158$\times 10^{-3}$ m^3/m^2/day with an average of 133$\times 10^{-3}$ m^3/m^2/day. While the designed lined portions exhibited lower unit seepage losses, ranging from 26 to 39 $\times 10^{-3}$ m^3/m^2/day, with an average of 32 $\times 10^{-3}$ m^3/m^2/day.

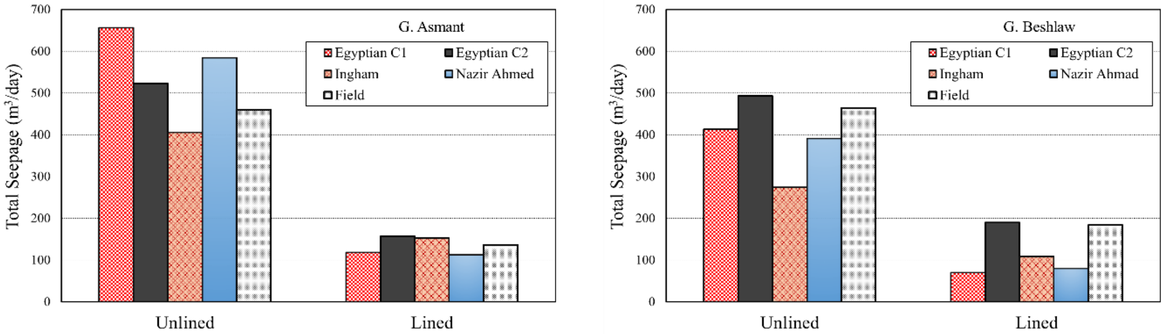
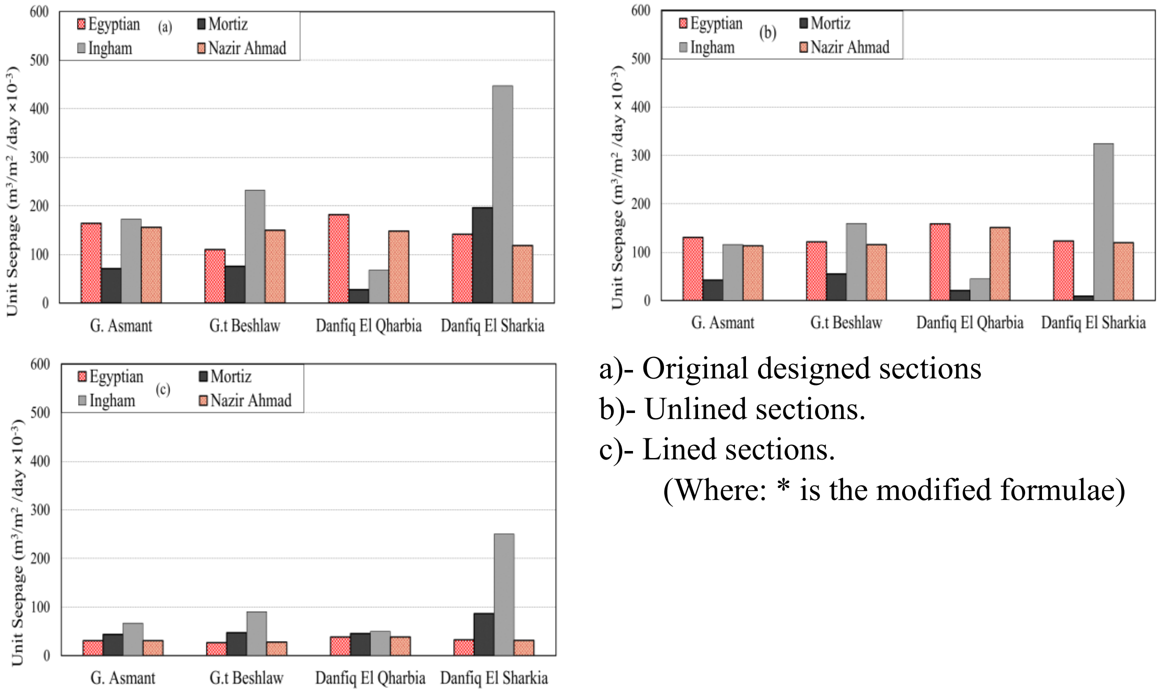


Figure 7. Seepage losses; calibration between the empirical formulas and field measurements (Where; reach length = 100 m, C_1=0.0015 & C_2=0.0017).

Table 3: Calculated total seepage from the canals (m^3/day).

Canal	Section	Original					Unlined					Lined				
		Egyptian	Mortiz	Ingham	Nazir Ahmad	Egyptian	Mortiz	Ingham	Nazir Ahmad	Egyptian	Mortiz	Mortiz*	Ingham	Ingham*	Nazir Ahmad	Nazir Ahmad*
G. Asmant	1	645	504	1229	595	960	517	1361	680	172	87	283	1229	553	498	159
	2	849	439	1071	783	1079	407	1130	997	184	77	431	941	424	543	174
	3	846	349	851	821	1247	353	1021	1143	199	71	485	786	354	596	191
	4	2668	196	479	2590	3279	176	545	3025	629	71	1537	442	199	1881	602
	Tot.	5007	1487	3629	4788	6565	1452	4057	5854	1184	306	2736	3398	1529	3581	1126
G. Beshlaw	1	723	253	778	982	1766	364	885	1705	193	61	501	778	350	672	215
	2	264	419	1287	358	441	467	1379	420	61	56	167	1189	535	220	70
	3	1924	155	477	2613	1923	122	477	1790	443	56	1217	440	198	1604	513
	Tot.	2910	827	2545	3953	4130	954	2740	3914	697	173	1885	2407	1083	2479	799
Danfiq El-Gharbia	1	1946	402	980	1311	3302	552	1067	2175	362	92	414	934	420	881	282
	2	2714	296	722	2416	1891	365	755	4905	611	87	1323	688	310	1496	479
	3	2164	275	671	1995	3153	280	708	2964	523	82	1176	708	318	1291	413
	4	2441	204	500	2379	3012	184	568	2778	575	71	1408	600	270	1460	467
	Tot.	9266	1177	2873	8102	11358	1380	3098	12822	2070	333	4321	2929	1318	5128	1641
Danfiq El-Sharkia	1	835	694	1590	665	1168	687	1348	1034	194	103	382	1460	657	428	137
	2	374	890	2035	304	532	882	1813	472	92	99	188	1938	872	317	101
	3	220	1160	2653	179	256	1012	2186	231	50	94	105	2395	1078	175	56
	4	3302	300	685	2685	3207	256	564	3357	748	94	1573	618	278	2621	839
	5	561	607	1383	470	698	46	1207	635	136	88	297	1302	586	489	156
	6	1178	419	954	986	1028	42	794	1175	286	88	623	898	404	1026	328
	7	224	959	2186	188	224	41	1723	210	55	88	119	2058	926	195	63
	8	4040	226	515	3380	4040	41	406	3774	787	77	1854	418	188	3008	962
	Tot.	10735	5254	12001	8857	11154	3007	10042	10888	2349	731	5140	11089	4990	8260	2643
Tot.		27919	8747	21045	25700	33207	6972	19937	33469	6302	1543	14083	19823	8920	19403	6209



a)- Original designed sections
b)- Unlined sections.
c)- Lined sections.
(Where: * is the modified formulae)

Figure 8. Unit Seepage for Original, Existing Unlined, and Lined sections $m^3/m^2/day$.

Table 4: Unit Seepage for sections ($\times 10^{-3} m^3/m^2/day$).

Canal	Section	Original				Unlined				Lined			
		Egyptian	Mortiz	Ingham	Nazir Ahmad	Egyptian	Mortiz	Ingham	Nazir Ahmad	Egyptian	Mortiz*	Ingham*	Nazir Ahmad*
G. Asmant	1	138	108	262	127	139	75	197	98	32	66	117	32
	2	178	92	225	164	132	50	139	122	31	52	79	31
	3	171	70	172	166	130	37	106	119	30	43	59	30
	4	170	13	31	165	122	7	20	113	30	13	11	30
	Avg.	164	71	172	156	131	42	116	113	31	44	67	31
G. Beshlaw	1	102	36	110	139	139	29	70	134	27	35	50	28
	2	114	181	557	155	122	129	382	116	26	98	232	28
	3	114	9	28	155	102	6	25	95	26	13	12	28
	Avg.	110	75	232	150	121	55	159	115	26	47	90	28
Danfiq El-Gharbia	1	326	67	164	220	313	52	101	206	61	98	116	60
	2	144	16	38	129	59	11	24	153	32	30	27	32
	3	131	17	41	121	139	12	31	131	32	32	32	32
	4	126	11	26	123	122	7	23	112	30	23	23	31
	Avg.	182	28	67	148	158	21	45	151	39	46	50	39
Danfiq El-Sharkia	1	151	125	287	120	152	89	175	134	35	73	154	21
	2	140	332	759	114	146	242	497	129	34	144	422	33
	3	149	786	1796	121	138	544	1174	124	3٤	248	945	33
	4	149	14	31	121	117	9	21	122	34	17	16	33
	5	136	147	335	114	134	9	232	122	33	84	184	33
	6	136	48	110	114	103	4	80	118	33	40	60	33
	7	136	580	1323	114	127	23	972	118	33	209	726	33
	8	159	9	20	133	127	1	13	118	31	12	10	33
	Avg.	142	196	447	118	123	9	324	119	32	86	315	31
T. Avg.		150	92	230	143	133	32	161	125	٣٢	56	114	32

4.2 Evaporation Losses

The total annual averages of evaporation losses were calculated using Eq. (6), as shown in Fig. (9). The results show that the total evaporation losses for original, existing unlined, and lined canals are 1166, 1408, and 941 m^3/day, respectively. The evaporation losses represent approximately 0.036%, 0.043%, and 0.029% of the canal's total discharge for the three conditions of canals.

In case of unlined canals, Danfiq El Sharkia has the highest evaporation rate, 474 m^3/day (44.63 m^3/day/km), while Ganapyt Beshlaw has the lowest one, 184 m^3/day (31.19 m^3/day/km). Furthermore, in the case of lined canals, Danfiq El Sharkia has the highest evaporation rate too, 367 m^3/day (34.56 m^3/day/km), while Ganapyt Asmant has the lowest one, 124 m^3/day (18.1 m^3/day/km). Canal's lining could save about 154.0, 48.0, 156.0, and 108.0 m^3/day at Ganapyt Asmant, Ganapyt Beshlaw, Danfiq El Gharbia, and Danfiq El Sharkia, respectively. These significant differences are attributed to several factors such as weather conditions, water temperature and depth, humidity levels, and other design characteristics of each canal. The evaporation loss represents 4.18%, 4.20%, and 14.93% of the total seepage loss in case of original, exist unlined and lined canal; respectively.

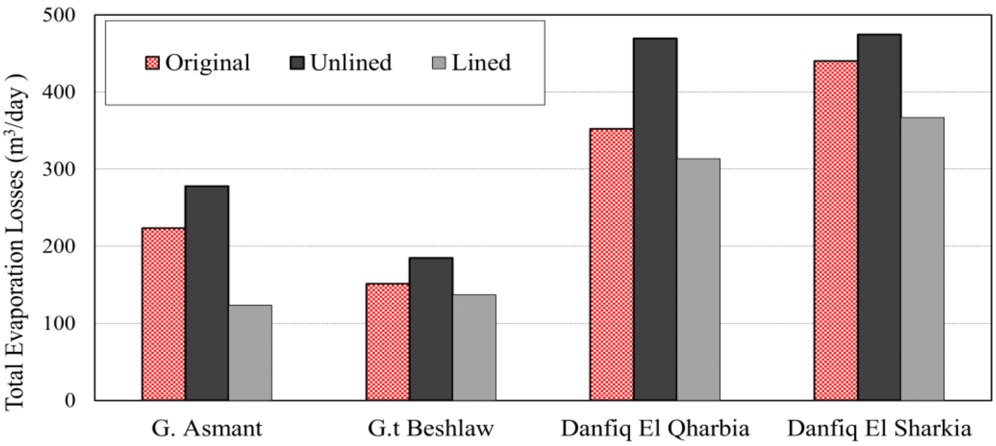


Figure 9. Total Evaporation Losses (m^3/day).

Several sources of uncertainty may affect the accuracy of the reported results. These include variability in soil type and permeability along the canal stretch, measurement errors during ponding tests, weather fluctuations affecting evaporation rates, and human errors in data recording. Furthermore, the assumption of steady-state flow conditions may not fully reflect field dynamics. Despite efforts to calibrate empirical equations with field data, some deviation may persist due to inherent site heterogeneity and methodological limitations. Future studies should consider longer test durations to strengthen result validity.

4.3 Error Analysis

To evaluate the accuracy of the seepage measurements obtained through the ponding test, a quantitative error analysis was conducted by comparing the measured losses to those estimated using empirical formulas. Specifically, for the Egyptian formula applied to the unlined and lined canal sections, the mean absolute error (MAE) was found to be approximately 381 m³/day, and the root mean square error (RMSE) was 442 m³/day. The percentage error ranged from 4% to 6% across different canal sections. These discrepancies are attributed to factors such as local construction defects, variations in lining quality, and heterogeneity in soil properties. Despite these variations, the overall error margins remain within acceptable engineering limits, supporting the reliability of the ponding test as a valid calibration tool for empirical models. This analysis also highlights the importance of site-specific adjustments when applying standard formulas to estimate seepage losses.

5. Conclusions

This study showed that canal lining can significantly reduce seepage losses, almost by 81%, to improve irrigation efficiencies in the dry areas. While evaporation losses were minimal, lining further reduced such losses. From the study findings, we strongly recommend stating large-scale canal lining programs with continuous monitoring and maintenance at intervals to sustain water savings and irrigation performance. The rehabilitation of lined canals in the Nakada area might potentially irrigate about 4,370 more acres. This is better water resource utilization, which in turn augments agricultural production and equitable water distribution.

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